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# Microgrids and Heterogeneous Power Quality and Reliability: Matching the Quality of Delivered Electricity to End-Use Requirements

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## Disclaimer

**Paper**

# Microgrids and Heterogeneous Power Quality and Reliability

## —— Matching the Quality of Delivered Electricity to End-Use Requirements——

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This paper describes two stylized alternative visions in popular currency of how the power system might evolve to meet future requirements for the high quality electricity service that modern digital economies demand, a supergrids paradigm and a dispersed paradigm. Some of the economics of the dispersed vision are explored, and perspectives are presented on both the choice of homogeneous universal power quality upstream in the electricity supply chain and on the extremely heterogeneous requirements of end-use loads. It is argued that meeting the demanding requirements of sensitive loads by local provision of high quality power may be more cost effective than increasing the quality of universal homogeneous supply upstream in the grid. Finally, the potential role of microgrids in delivering heterogeneous power quality is demonstrated by reference to two ongoing microgrid tests in the U.S. and Japan.

**Keywords** : cogeneration, dispersed storage and generation, power quality, power system economics.

## 1. INTRODUCTION

Consumption of electricity continues to grow in developed economies. For example, U.S. consumption of electricity is fore-cast to increase roughly by half over the current quarter century(1). Most analysts anticipate a role for *dispersed resources* in the much expanded generation capacity that will be required to meet the seemingly inexorably expanding electricity demand. Further, given the urgency of tackling the climate change problem, many of these assets must be carbon-free renewables or very efficient fossil-fired technologies. Herein, dispersed resources are considered to be generation with capacities too small to directly participate in wholesale markets, e.g. ≈<1-2 MW, such as small-scale combined heat and power (CHP) installations, photovoltaic arrays (PV), small fuel cells, local heat and electricity storage, etc.

The dominant theme of current thinking about the development of such dispersed generation is in terms of the value it can provide to its owner and to the wider existing power system, and the technical challenge of integrating it into the current power system. But the existence of dispersed energy sources and controlled sinks, possibly grouped in microgrids that exercise some autonomy, may ultimately more fundamentally change the nature of the familiar grid itself. Rapid (if not accelerating) technological change surrounds us, and the nature of the power system will inevitably evolve over time. Emerging dispersed resource technologies cannot be divorced from this process; indeed, they may serve as one of its many engines. Trends emerging in the power system suggest that the centralized paradigm that has dominated power systems for the last century may eventually be replaced, or at least diluted, by an alternative one in which control is more dispersed, and universal quality of service is replaced by heterogeneous service locally tailored to the end-use requirements.

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## 2. BACKGROUND

In developed economies, the current power delivery paradigm has been in place worldwide for a long time, i.e. since the emergence of polyphase AC systems around the turn of the last century. In outline, this dominant paradigm consists of large-scale central station gener- ation, long distance bulk transmission of energy over centrally operated high voltage meshed grids, and local distribution at ever lower voltages through simpler partially locally managed, uni-directional radial lines. A key feature of this structure is that universal service power is, in principle, delivered at a consistent level of power quality and reliability (PQR) throughout large regions. For example, PQR targets are consistent virtually all across North America, and where standards cannot be met, it is usually the result of a local technical difficulty and not the outcome of a deliberate attempt to deviate from the universal norm. This predictability of service delivers an enormous economic benefit because all types of electrical equipment can be built to meet a homogeneous universal standard, and indeed the traditional paradigm has served developed economies well for a very long period during which the uses for and consumption of electricity have increased enormously, even at times spectacularly. As is often observed, modern life as we currently experience it seems impossible without such ubiquitous, universal, reliable, high- quality power. To be clear, higher PQR is unequivocally better than lower, i.e. it is an economic *good*; the current dilemma springs from the technical challenge and cost of improving PQR, not from any question about its desirability.

Changes in expectations for the power supply system on both the supply and demand sides are bringing us to a turning point in its evolution and quite possibly to the first paradigm shift in over a century. Improving traditional universal service to the point at which it can meet the requirements of sensitive or modern digital loads may be unnecessarily costly. The changes on the demand-side result from our seemingly unquenchable thirst for electricity in an emerging digital age that is significantly tightening our PQR requirements for some applications, while on the supply-side, concerns about terrorism, restrictions on system expansion, and the uncertainties of volatile markets in energy-short times bring our ability to maintain current standards into doubt(2).

## 3. ALTERNATIVE VISIONS

The schematics in Figs. 1 and 2 below show two alternative visions in current currency of how the power system might be retooled to provide high PQR, a supergrids view, and a dispersed paradigm. These are only two stylized representations of many possible paths, and full justice cannot be given here to the technical intricacies of any specific vision. The intent is only to contrast in a comprehensible way the central themes of multiple divergent alternatives. For more detail on a supergrids leaning view, see Gellings et al, Amin, or Amin and Wollenberg(3,4,5). A comprehensible vision for a dispersed grid is presented by the European Commission, or, for other voices from the dispersed camp, see Lasseter or Marnay and Venkataramanan, but these are by no means the only contributors to this ongoing debate(6,7,8).

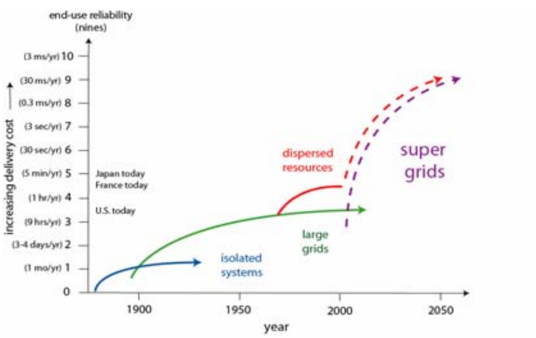


Fig. 1. Supergrids vision.

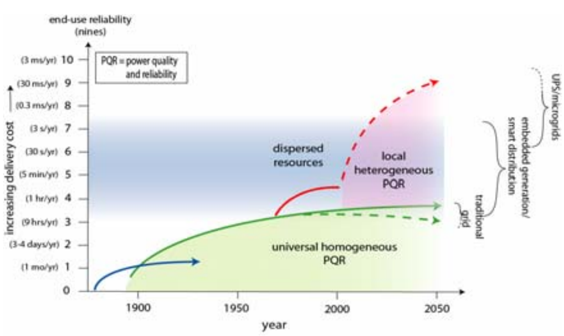


Fig. 2. Dispersed grid vision.

The x-axes in both figures roughly cover the historic development of the existing power supply system, while the y-axes in both figures simply show availability in nines together with the equivalent annual expected outage duration. Other dimensions of PQR are harder to portray so they do not appear explicitly. But somewhat more abstractly, similar arguments can also be made with respect to them. Typical U.S. electricity service today is in the 3-4 nines range or a few hours of expected annual outage, which is poor performance relative to most developed countries. Japan, for example, achieves significantly higher reliability, approaching 5 nines or only a few minutes of expected annual outage, and in certain favorable regions, even higher performance is achieved.[1] As the *large grids* curve shows, over the last century, improved technology and interconnection over larger areas have steadily improved reliability. Nonetheless, in the U.S. case, following the northeast blackouts of the 1960s and 1970s, the need to provide local backup sources for critical loads was recognized and introduced into building codes and other regulations. A formal dispersed electricity supply system shown by the solid *dispersed resources* curve was thereby established, primarily in the form of the now ubiquitous diesel back-up generator.

**3.1 SUPERGRIDS VISION** The steady rise of sensitive loads over more recent times has led to widespread additional use of backup generators, uninterruptible power supplies, and other equipment to ensure high quality energy supply to such loads. Protecting them from service that deviates from standards is at the heart of the divergence in visions. There are actually two types of sensitive loads, ones motivated by the business importance of high value added or "mission critical" loads, e.g. data centers, and ones required to guarantee vital services, most importantly those required for emergency response. The supergrids camp holds that deployment of diverse suites of new technologies can significantly improve the performance of all elements of the power supply chain built around the traditional paradigm, as shown in Fig. 1 by the lower dashed line. Despite the goal of across-the-board technical improvement, much of the improvement inevitably must come in the distribution system because most outages occur there, over 90% in the case of the U.S. It forms the most vulnerable link because of its sheer size and dispersion, as well as its exposure to the myriad hazards of extreme weather, accidents, and mischief. Even in the supergrids view, inevitably there will be end-uses that require PQR beyond even the performance of the much enhanced delivery chain, but these can be kept to a minimum. Much attention is paid in this framework to the risk that dispersed resources pose to the overall supply chain. The extra locally provided PQR is shown in Fig. 1 by the upper dashed line. In other words, only the increased performance between the two dashed lines is provided by dispersed resources, representing a small share of all the delivered energy.

**3.2 DISPERSED GRID VISION** Fig. 2 shows an example schematic of a dispersed vision whose key feature is increased reliance upon rather than minimization of dispersed resources. In this view, traditional universal grid service is not improved significantly but rather holds steady at current levels. Sensitive loads are then increasingly served locally in two ways: first, improvements in the distribution system (as in the supergrids vision) are deployed to improve on the existing system's weakest link; and second, widespread use of supply and other resources close to sensitive end-uses protect them at the levels they demand. Finally, in this paradigm, as the lower dashed traditional grid line shows, some deterioration of universal PQR is possible. This phenomenon is discussed below.

**3.3 VISION COMPARISON** A number of key differences between the two paradigms should be noted.

1. In the dispersed vision, the performance of generation and high voltage transmission is not called upon to achieve significant improvements, although conversely they are not precluded. The

[1] Note that the 14 August 2006 Tokyo blackout nonetheless demonstrates the fragility of electrical service, even in Japan.

level of bulk power PQR is determined somewhat independently of end-use requirements based on technical, economic, and security realities. This is perhaps the most important distinguishing feature of the dispersed vision, i.e., it does not depend on significant technical breakthroughs and investment far upstream from the growing energy use and sensitive loads that are the root cause of the current dilemma.

2. Improvements in the distribution system are envisaged in both visions. To some extent, they both depend not only on better distribution technology per se, but also on the existence of local generation embedded in the distribution system that permits the provision of reliable service somewhat independently of the upstream power system. Quite possibly in both visions, the distribution system might be able to function without grid power for some periods, deliberately islanding and reconnecting as necessary or beneficial. In this regard, the difference between the two paradigms is simply a matter of degree, with the dispersed vision depending much more heavily on improved distribution rather than improved high voltage transmission.

3. In the dispersed paradigm, local to actual end-use loads (one might say in current terminology, on the customer side of the meter), a wide range of additional technologies is employed to ensure adequate service to loads requiring higher-than-universal-level PQR than is being delivered at the meter. The technologies in question include small generators, renewably powered or fossil thermal, possibly with CHP, storage devices, demand control, opportunistic local resources such as low quality non-traditional fuels, power conditioning equipment, etc. In some cases, this equipment may be clustered in electronics based microgrids.

4. This dispersed paradigm represents a major break with tradition in the sense that PQR of electricity arriving at customer meters might vary with local conditions, and the PQR at end-use devices varies even more so, based on local requirements. This aspect can be thought of, as is shown in the diagram, as delivered electricity, being of the familiar universal homogenous PQR upstream, but increasingly heterogeneous down-stream depending on the sensitivity or value added of various end-uses. Further, the overlapping braces to the right of Fig. 2 are intended to show that levels of PQR delivered and how they are achieved are far from resolved, and no definitive dividing line between sources is yet apparent.

5. It should be noted that in the dispersed paradigm, the optimal level of upstream homogeneous PQR could potentially be even lower than current standards, as shown by the declining dashed traditional grid line, whereas in the supergrids paradigm, all links in the supply chain must improve. In other words, in the dispersed vision, if the demanding requirements of sensitive loads are satisfied downstream, then our expectations for the centralized grid upstream might well be lower than today, rather than increase significantly, as in the supergrids view. This concept is explored further in section 5 below.

## 4. HOMOGENEOUS VS. HETEROGENEOUS PQR

While outages may be scheduled for periodic maintenance operations on the electrical system, unscheduled outages are generally much more disruptive and threatening to people and property. Outages' effects include unavailability of certain services and processes, such as refrigeration, manufacturing, etc., plus dependence on on-site backup generation, which is typically costly and environmentally damaging.

In contrast, deterioration in power quality has mixed and less dramatic effects, even if important, and in some cases, costly. It is caused by deviations in the features of the electrical power delivered to the load, such as voltage sags, swells, harmonics, imbalances, etc., which are triggered by periodic switching operations or by faults in the electrical systems due to weather, wildlife, human errors, etc. If power quality events do not lead to service loss, they become important only when they trigger degradation in end-use service or equipment performance or durability. Thus, from an end-user perspective, both low power quality and poor reliability cause consequences and costs, while the scale and drama of events might be quite different.

The notion of heterogeneous PQR (HeQ) is a somewhat new concept in power systems. It exists to some extent in both visions described above, but is central to the dispersed vision, and the nature of HeQ's role in the dispersed paradigm occupies the remainder of this paper.

The essence of the supergrids paradigm is homogeneous PQR (HoQ). In principle, near perfect electricity is delivered everywhere in the system at all times; nonetheless, HeQ creeps in because the expensive investments necessary to improve PQR are unlikely to be made universally and evenly across the system. Indeed, some heterogeneity is routinely tolerated, although it is rarely recognized as such. For example, remote feeders are restored more slowly than ones in densely populated areas; conversely, some key circuits receive exceptional attention, notably ones on which emergency or other vital services are interconnected. These limitations notwithstanding, the objective of the supergrids vision is an extension of the current paradigm in which HoQ is dramatically improved.

In the dispersed vision, as shown in Fig. 2, PQR diverges from the standard downstream of the substation. Safe and economic operation of the high voltage meshed grid relies as it always has on tight standards and centralized operation; however, downstream, PQR becomes increasingly heterogenous, with delivered electricity to the end-use potentially diverging considerably. Two obvious questions arise: 1. Given that locally, HeQ is tailored to end-use loads and can deviate in either direction from the upstream HoQ, how should the standard for upstream HoQ be chosen? And 2., why does HeQ make sense at the end-use level? The following two sections address these two questions.

## 5. CHOOSING THE HoQ STANDARD

As explained above, while the ideal is rarely achieved in practice, the prevailing current paradigm is to universally provide HoQ to every load in the network. In the dispersed vision, this remains true upstream in the grid.

Fig. 3 conceptually shows a possible approach to picking the optimum universal target PQR level for the economy to adopt. Again, PQR is represented by simple availability because other aspects of PQR are more difficult to quantify and visualize. Reliability and PQR are herein used very loosely and interchangeably. The x-axis, corresponding to the y-axes of Figs. 1 and 2, shows increasing PQR on a pseudo-log scale, with approximately the lowest reliability we can currently imagine as acceptable to a modern economy to the left and perfection to the right. Again, the U.S. lies between three and four nines, while the world's most reliable systems approach the five nines range.

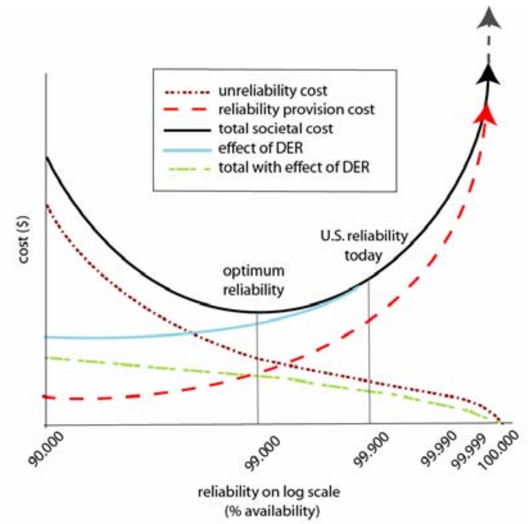

Fig. 3. Finding optimal HoQ.

The y-axis shows the societal cost of providing PQR. This cost has two components, the cost of providing reliability and the cost of the residual unreliability, with the sum of the two representing the total societal cost. The dotted unreliability cost curve shows what we all know well; namely, that poor PQR costs the economy dearly. These costs might be high to the left, where many developing countries find themselves, and would fall to zero on the right, if perfection could be achieved. The dashed reliability provision cost curve shows the cost of providing PQR. Better service incurs higher costs of two types, the equipment costs of a physically more robust system and the foregone electricity trade prevented by conservative grid operations imposed for reliability reasons. While the relative magnitudes of the two cost components are unclear, the latter may well be the larger. The nature of the curves in Fig. 3 is purely conceptual and no comprehensive data are available to construct such curves. Nonetheless, it is quite clear that costs will be asymptotic as the grid nears unattainable perfection.

The solid total societal cost curve simply represents the sum of the two curves, the cost consequences of having an imperfect system plus the out-of-pocket cost of providing the prevailing level of PQR. The societal optimum is clearly at the point of minimum total social cost, which in Fig. 3 occurs to the left of the current U.S. target of about 99.99%, and even further to the left of Japan's. Developed economies have generally chosen to push reliability to the right in Fig. 3, with relatively little consideration of the cost tradeoffs implicitly involved. It might also be observed that most developed countries have focused heavily on the unreliability cost curve with relatively little attention paid to the cost of providing PQR; however, this is not to say that reliability has been pursued at any cost because clearly choices are made; e.g., the use of overhead lines rather than under-grounding shows that limits to expenditures in pursuit of reliability indeed exist and trade-offs are implicitly made.

The dispersed paradigm would tend to have the effect of lowering the unreliability cost because loads that require high PQR are still provided for locally, making systems more resilient. It is pure speculation at this point what the net effect would be, but one credible possibility is that the societal optimal could be pulled leftwards as shown by the grayed-out versions of the curves.

## 6. END-USE HEQ

In the power sector, understanding of the time and spatial differentiation in the value of electricity is familiar, and efforts have also been made to estimate the contribution of various end-uses to system peak loads[9]. Consideration of how the value electricity varies given the PQR requirements of the end-use served is much less common.

Various indices for measuring PQR are often used in quantifying levels of electrical service[10]. While technical analysis of electricity service PQR can be sophisticated, by contrast, analysis of the economics of PQR is at best rudimentary, which makes it difficult to relate its importance to the energy side of power systems. In other words, it tends to be quite easy to measure the energy value of electricity but hard to measure its PQR value.

Nonetheless, it is intuitively appealing to think that delivering PQR tailored to the requirements of end uses, as is the case in the dispersed paradigm, can generate higher economic benefits than universal PQR that never quite matches the requirements. Consider the pyramid shown in Fig. 4, which illustrates how various electricity uses might be classified according to their PQR requirements. Some common loads, such as pumping, are widely agreed to have low PQR requirements and appear at the bottom of the pyramid, and vice-versa. Other loads can be much harder to classify; e.g., refrigeration is reschedulable in many applications, but might be critical in others, such as medication storage. At the top of the pyramid, the exposed peak above current standards shows that not all requirements are currently met. The layout of enduses is highly speculative and simply intended to show how HeQ might be considered. More important is the pyramid shape itself. It is clearly not a natural law that low PQR demanding loads vastly outnumber critical ones; however, if we behave in an economically rational manner, we would attempt to make them so. In other words, serving the low requirements loads at the bottom is cheap, and vice-versa for the sensitive loads at the top. We should be trying, therefore, to classify as much of the overall load in the base as possible. For example, for equipment considered a sensitive load, it is often only a small share of the energy that is essential, e.g. to run controls, while much of the energy consumed could be of relatively low quality. In such cases, two qualities of service might be delivered to the respective parts of the device.

Analysis of PQR in a form like the pyramid could potentially lead to the clustering of like PQR loads on certain circuits and the provision of electricity of appropriate quality to that circuit, and the disaggregation of some loads into constituent parts of varying PQR requirements. At the same time, the effective provision of high PQR locally to sensitive loads could potentially lower the societal optimum for grid service, as mentioned above.

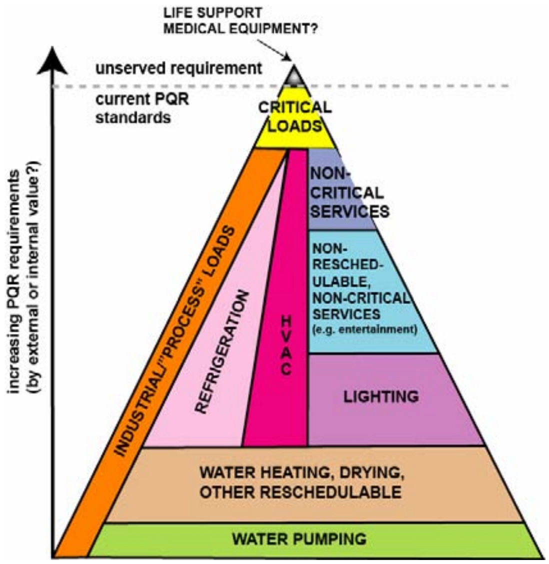


Fig. 4. A HeQ pyramid.

Systems could potentially supply multiple service qualities to different parts of the pyramid delivering significant economic benefits, much of which may be in the form of lower requirements for upstream HoQ. Further, the following observations are offered.

1. Little analysis or data collection has been done to establish the PQR requirements of loads.

2. Matching the PQR delivered to the requirements of the end-use can potentially meet our goals at lower cost than universal PQR.

3. A wise approach would disaggregate loads such that high PQR loads are minimized because they are the costly ones to serve.

4. Delivering heterogeneous PQR poses some practical problems as well as benefits. All existing electrical equipment in the industrialized world is designed and manufactured with expectations of high and homogeneous PQR. Deviations from this norm will likely incur consequences and costs that are currently unknown.

5. Lastly but importantly, the concept of universal service is not only a technical one, but also a legal one. The legal basis under which different service quality is delivered to various sites is not yet clear, but it is reasonable to assume that tariffs would necessarily reflect the delivered power quality.

## 7. MICROGRIDS

In Fig. 2, HeQ is provided locally by embedded generation within the distribution system, by on-site generation and power conditioning equipment, and by microgrid technology. A microgrid is a local cluster of sources and sinks that operates semi-autonomously of the grid, being able to island and reconnect as circumstances dictate. Providing appropriate HeQ to match the requirements of end-uses is a central feature of some microgrid concepts, notably the Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid, and the NTT Facilities microgrid being demonstrated in Sendai, Japan, shown in figure 5 [11,12,13,14]. In the case of the CERTS Microgrid, HeQ is provided by segregation of loads on separate circuits. Critical loads are placed near reliable sources in a grouping that can disconnect and operate islanded without need of fast electrical device controls. In the case of the Sendai microgrid, DC loads are served directly on a circuit dedicated to critical telecommunications equipment, and multiple qualities of .AC services are provided.

Fig. 5. Sendai microgrid installation. (Source: NTT Facilities)

## 8. CONCLUSIONS

Our current power system may be entering a period of significant fundamental change of a kind not seen for a century, and currently there are conflicting visions of what form the reshaped industry may take. Some of the uncertainty revolves around the requirements of modern economies for high quality electrical service and the most cost effective way of providing it. One viable possibility is through local control of PQR in microgrids. In addition to the technology needed to enable such a transition, effectively managing it will require new analytic tools and new regulatory regimes. Some of the economic and legal issues will require consideration of aspects of electricity service that have heretofore been for the most part beyond our economic capabilities. Development of new methods of analysis must be undertaken to confront the challenge.

## 9. ACKNOWLEDGMENT

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